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Cosmological gravitino problem confronts electroweak physics

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Abstract

A generic feature of gauge-mediated supersymmetry breaking models is that the gravitino is the lightest supersymmetric particle (LSP). In order not to overclose the universe, the gravitino LSP should be light enough ($\lesssim 1$ keV), or appropriately heavy ($\gtrsim 1$ GeV). We study further constraints on the mass of the gravitino imposed by electroweak experiments, *i.e.*, muon $g-2$ measurements, electroweak precision measurements, and direct searches for supersymmetric particles at LEP2. We find that the heavy gravitino is strongly disfavored from the lower mass bound on the next-to-LSP. The sufficiently light gravitino, on the other hand, has rather sizable allowed regions in the model parameter space.

Although the standard model (SM) of particle physics is in good agreement with the results of high energy collider experiments, we expect that new physics beyond the SM lies in the TeV scale, which stabilizes the weak scale by protecting the Higgs boson mass from radiative corrections. The Minimal Supersymmetric extension of the SM (MSSM) is the most promising candidate of new physics beyond the SM. In the MSSM, quadratic divergences in the radiative corrections of the Higgs boson mass are canceled between the contributions from the particles in the SM and from their supersymmetric partners. However, since exact supersymmetry (SUSY) predicts an unrealistic degenerate mass for the ordinary particle and its superpartner, SUSY must be broken softly. It is, therefore, important to understand the mechanism of SUSY breaking and study constraints on the soft SUSY breaking terms from phenomenological points of view. In particular, serious constraints come from the processes mediated by flavor changing neutral current (FCNC), such as K^0-$\overline{K^0}$ mixing, which require rigorous degeneracy of the sfermion masses in the flavor space.

There are a few classes of SUSY breaking scenarios. Among them, gauge mediated SUSY breaking (GMSB) models [1] have been motivated to satisfy the phenomenological constraints on the soft SUSY breaking parameters from the FCNC processes. In general, the GMSB models consists of (i) a secluded sector where supersymmetry is dynamically broken, (ii) the visible sector in which all the MSSM fields live, and (iii) the messenger fields that transmit the effect of SUSY breaking from the secluded sector to the visible sector via the ordinary gauge interactions. Since the gauge interaction is flavor blind, there is no dangerous flavor violating source in the SUSY breaking parameters, and the phenomenological constraints from FCNC are satisfied.

The most striking feature of the GMSB models is in the fact that the gravitino is the Lightest Supersymmetric Particle (LSP)[1]. In general, the energy density of the stable gravitinos could exceed the critical density of the universe, which is so called the cosmological gravitino problem [2]. Since the gravitinos are produced more abundantly as temperature becomes higher, the gravitino problem posses a constraint on the reheating temperature of the inflation T_R. The upper bounds on

[1] We assume R-parity conservation.

T_R for different mass scales of the gravitino mass $m_{3/2}$ are given by [3, 4]

$$T_R \lesssim \begin{cases} 100 \text{ GeV} - 1 \text{ TeV} & \text{for } 1 \text{ keV} \lesssim m_{3/2} \lesssim 100 \text{ keV} \\ 10^8 \text{ GeV} \times \left(\frac{m_{3/2}}{1 \text{ GeV}}\right)\left(\frac{m_{\widetilde{B}}}{100 \text{ GeV}}\right)^{-2} & \text{for } m_{3/2} \gtrsim 100 \text{ keV} \end{cases}, \quad (1)$$

where $m_{\widetilde{B}}$ denotes the bino mass. The reheating temperature for the heavier gravitino mass region in (1) is compatible with the ordinary inflation scenario where it is typically given by $T_R \gtrsim 10^8$ GeV. On the other hand, for the lighter gravitino mass region, T_R is too low, so that a certain substantial entropy production mechanism below T_R should be introduced [3]. It should be noted that the overclosure problem due to the gravitino LSP is evaded irrelevantly to T_R if the gravitino mass is small enough, say, $m_{3/2} \lesssim 1$ keV [2].

The heavier gravitino LSP ($m_{3/2} \gtrsim 100$ MeV) is also imposed a constraint associated with the Next-to-LSP (NLSP). The lifetime of NLSP could be comparable with the Big-Bang Nucleosynthesis (BBN) era, so that the decay of the NLSP may affect the abundance of the light elements in the universe. The constraints on $m_{3/2}$ and T_R are examined in ref. [4] taking into account this effect. The allowed regions are given by $m_{3/2} = 5 - 100$ GeV and $T_R = 10^9 - 10^{10}$ GeV when the stau is the NLSP. If the neutralino is the NLSP, it gives rise to more severe constraints on the reheating temperature because of its small annihilation cross section and relatively larger abundance as compared to the stau NLSP.

In this letter, we study constraints on the parameter space of GMSB, taking into account the results of muon $g-2$ experiments at BNL [5], the electroweak precision measurements at LEP and SLC [6], and direct searches for supersymmetric particles at LEP2 [7, 8, 9]. We would like to pay a special attention to whether there are further constraints on the gravitino mass scale from those experimental data, in addition to the cosmological constraints. In the following, we assume that any entropy production mechanisms do not exist below T_R, so that the cosmologically favored gravitino mass scale is limited to $m_{3/2} \lesssim 1$ keV [2] or $m_{3/2} = 5 - 100$ GeV [4]. We will show that the allowed region of the gravitino mass is sensitive to the muon $g-2$ and the NLSP search experiments. The heavy gravitino is allowed only in a small corner of the parameter space.

Let us first briefly review the parameter set of the GMSB models to fix our notation. The fundamental parameters in the GMSB models can be summarized as follows [10]:

$$M_m, \ \Lambda, \ k, \ N_m, \ \tan\beta, \ \text{sgn}(\mu). \quad (2)$$

The first four parameters are related to the SUSY breaking sector and the messenger sector. M_m is the mass scale of messenger fields and Λ denotes the scale parameters of soft SUSY breaking terms in the MSSM sector at M_m, where the messenger fields are integrated out. The positivity of the messenger squared mass requires $\Lambda < M_m$ [10]. The dimensionless parameter $k(\leq 1)$ is the ratio of the fundamental scale of SUSY breaking and the SUSY breaking scale felt by the messenger fields. The integer N_m represents the number of messenger fields which transform as $\mathbf{5} + \bar{\mathbf{5}}$ (or $\mathbf{10} + \bar{\mathbf{10}}$) in SU(5), so that the gauge coupling unification is preserved. $\tan\beta$ is defined by the ratio of v_u and v_d which are the vacuum expectation values of the Higgs fields with the hypercharge $Y = 1/2$ and $-1/2$, respectively. The last parameter in (2) is the sign of the higgsino mass μ. The soft SUSY breaking parameters in the MSSM at M_m are expressed in terms of the parameters in (2), and those at the weak scale can be obtained by solving the renormalization group equations (RGEs). The gravitino mass is given by

$$m_{3/2} = \frac{\Lambda M_m}{k\sqrt{3}M_{\rm Pl}}, \tag{3}$$

where $M_{\rm Pl} = 2.4 \times 10^{18}$GeV is the reduced Planck mass.

Next we summarize the set of experimental data which we adopt in our analysis. The anomalous magnetic moment $(g-2)$ of the muon has been measured precisely at BNL. Using the convention $a_\mu = (g-2)/2$, the current result is given as [5]

$$a_\mu(\text{expt}) = 11659203(8) \times 10^{-10}. \tag{4}$$

Theoretical prediction on a_μ has a large uncertainty due to the hadronic contributions. There are a number of estimations on the hadronic contributions using various methods. As the SM prediction in our study, we use

$$a_\mu(\text{th}) = 11659177(7) \times 10^{-10}. \tag{5}$$

Then the difference between the experimental measurement and the SM prediction is given as

$$\Delta a_\mu = 26(10) \times 10^{-10}, \tag{6}$$

which shows 2.6-σ discrepancy. We require that the SUSY contributions to the muon $g-2$ explain this difference.

The supersymmetric contributions to the muon $g-2$ come from 1-loop diagrams mediated by (i) chargino-sneutrino exchanges and (ii) neutralino-smuon exchanges.

The size of effects from these diagrams is proportional to $\tan\beta$, while the sign becomes consistent with (6) if the sign of μ parameter is positive [11].

The electroweak precision measurements of Z-pole observables at LEP1 and SLC, and the W-boson mass at LEP2 and Tevatron, may also constrain the parameter space of the GMSB models. The electroweak data which we use in our study consist of 17 Z-pole observables and the W-boson mass. The Z-pole observables include 8 line-shape parameters ($\Gamma_Z, \sigma_h^0, R_\ell, A_{\rm FB}^{0,\ell}(\ell = e, \mu, \tau)$), two asymmetries from the τ-polarization data (A_τ, A_e), the decay rates and the asymmetries of b and c quarks ($R_b, R_c, A_{\rm FB}^{0,b}, A_{\rm FB}^{0,c}$), and the asymmetries measured at SLC ($A_{\rm LR}^0, A_b, A_c$). The experimental data of these observables are summarized in ref. [6]. Taking into account the data for the top-quark mass from Tevatron[12], $\alpha_s(m_Z)$ [13] and $\alpha(m_Z^2)$[14], we find that the SM best fit gives $\chi^2/(\text{d.o.f.}) = 21.4/(21-4)$ (21% CL). The supersymmetric particles affect the electroweak observables through the universal gauge-boson propagator corrections (oblique corrections) and the process specific vertex or box corrections at 1-loop level. It has been shown that the contributions from squarks and sleptons to the electroweak observables always make the fit to the experimental data worse than the SM fit if these particles are as light as $\sim$ 100GeV [15].

In the GMSB models, the NLSP is either the lightest neutralino $\widetilde{\chi}_1^0$ or the lighter stau $\widetilde{\tau}_1$. As already mentioned, the BBN constraint favors the stau as the NLSP rather than the neutralino for the gravitino mass $m_{3/2} \gtrsim 100$ MeV [4]. The lower mass bounds on the NLSP in direct search experiments are given as [16]

$$m_{\rm NLSP} > \begin{cases} 55 \text{ GeV} & \text{for } \widetilde{\chi}_1^0 \text{ NLSP} \\ 77 \text{ GeV} & \text{for } \widetilde{\tau}_1 \text{ NLSP} \end{cases} . \tag{7}$$

In Fig. 1 we show the allowed region on the (Λ, M_m) plane from the direct search experiments of the NLSP in (7). In our analysis, we assume radiative electroweak symmetry breaking, which is induced by the top-quark contributions to the RGEs for (mass)^2 terms of the Higgs fields [17]. For simplicity, we fix the parameters k and N_m in eq. (2) by $N_m = k = 1$. We also choose $\mu > 0$ so as to be consistent with the muon $g-2$ constraint in (6). The $\tan\beta$ dependence is examined by varying its value as $\tan\beta = 3, 10, 30$ and 50. In the figure, the solid line expresses $M_m = \Lambda$, and we discuss the region of $M_m > \Lambda$ [10].

The conditions for radiative electroweak symmetry breaking exclude the dark regions labelled by “EWSB”. The excluded regions from the direct search limits

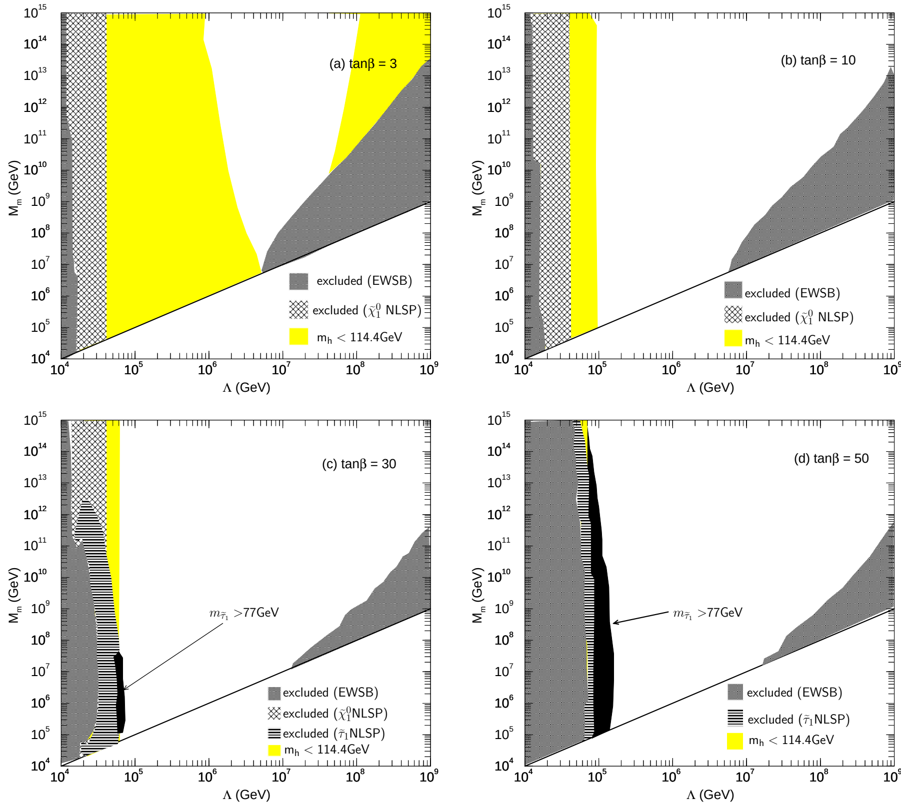

Figure 1: Allowed regions on the (Λ, M_m) plane from the radiative electroweak symmetry breaking condition and the NLSP direct searches for $\tan\beta = 3, 10, 30$ and 50. The solid line in each graph shows $M_m = \Lambda$. In the dark shaded regions (labeled "EWSB") electroweak symmetry is not broken radiatively. The excluded regions from the direct search limits on the NLSP ($\tilde{\chi}_1^0$ or $\tilde{\tau}_1$) are shown explicitly. The light shaded region corresponds to $m_h < 114.4$GeV. In the blank region above the $M_m = \Lambda$ line, the NLSP is the neutralino. There are the allowed regions from the direct search limit on the stau NLSP [16] in (c) and (d).

on the $\tilde{\chi}_1^0$- or $\tilde{\tau}_1$-NLSP in (7) are shown explicitly. In the blank region, the direct search bound on the $\tilde{\chi}_1^0$ NLSP in (7) is satisfied. In the analysis the lower mass bounds on the lighter chargino $m_{\tilde{\chi}_1^-} > 104$GeV [7] and the lightest Higgs boson $m_h > 91$GeV [8] from the LEP2 experiments are used as constraints, though they do not reduce the allowed regions of $\tilde{\chi}_1^0$ or $\tilde{\tau}_1$ NLSP in Fig. 1. It should be noted that the lower limit on the lightest Higgs boson mass $m_h > 91$GeV is valid in a very limited parameter space of the Higgs sector, and, in most of the parameter space, it coincides with the lower mass bound on the SM Higgs boson, $m_h > 114.4$GeV [9]. We find that, if $m_h > 114.4$GeV is used as constraint, the

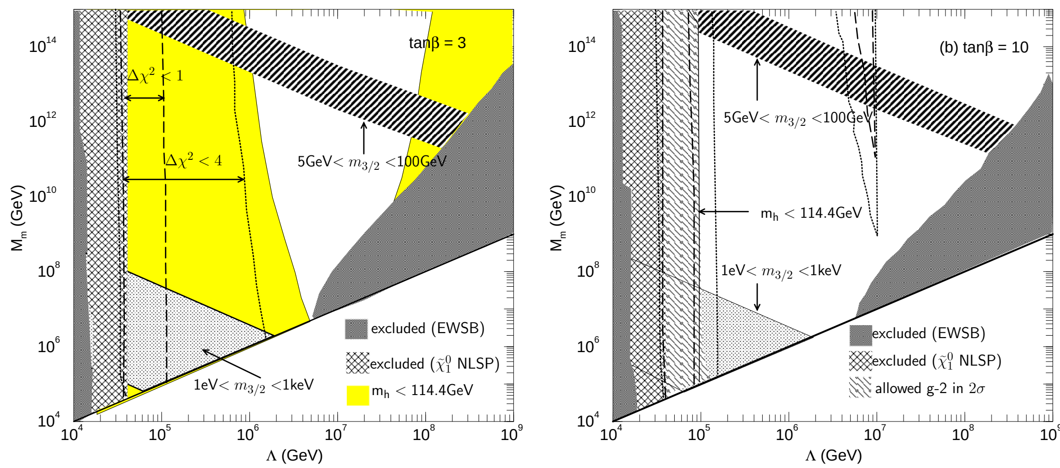

Figure 2: Constraints on the (Λ, M_m) plane from the electroweak precision measurements and the muon $g-2$ experiments for $\tan\beta = 3$ (a) and 10 (b). The gravitino mass range is shown for 1eV $< m_{3/2} <$ 1keV and 5GeV $< m_{3/2} <$ 100GeV. The enclosed regions by the dotted lines give $\Delta\chi^2 < 4$, while those by the long-dashed lines give $\Delta\chi^2 < 1$ for the electroweak precision data. The 2-σ allowed region of the muon $g-2$ experiments is shown explicitly in (b). In (a), the allowed region of the muon $g-2$ is hidden by the $\tilde{\chi}^0_1$ NLSP excluded region.

allowed region is significantly reduced for $\tan\beta = 3$ (Fig. 1(a)). It is remarkable that the allowed region of the stau NLSP appears only when $\tan\beta$ is rather large (Figs. 1(c) and (d)). Therefore, the heavier gravitino $m_{3/2} = 5 - 100$GeV for solving the cosmological gravitino problem [4] is strongly constrained from the stau NLSP search experiments.

Let us examine constraints on the GMSB models from the muon $g-2$ and the electroweak precision data for $\tan\beta = 3$ and 10 in Fig. 2. On the NLSP constraints, we superpose the gravitino mass ranges (1 eV $< m_{3/2} <$ 1 keV and 5 GeV $< m_{3/2} <$ 100 GeV) and the 2-σ allowed regions of the muon $g-2$ data in the (Λ, M_m) plane. The long-dashed and dotted lines indicate $\Delta\chi^2 \equiv \chi^2_{\rm SUSY} - \chi^2_{\rm SM} = 1$ and 4 in the fit to the electroweak precision data, respectively. It is easy to see that there is no allowed region of the muon $g-2$ data in Fig. 2(a) ($\tan\beta = 3$). As is already mentioned, the SUSY contributions to the muon $g-2$ are proportional to $\tan\beta$. If $\tan\beta$ is small, therefore, relatively light SUSY particles are required for sizable contributions to the muon $g-2$. Such parameter region in Fig. 2(a) is inconsistent with the direct search limit on the $\tilde{\chi}^0_1$ NLSP mass. If $\tan\beta$ becomes larger (Fig. 2(b)), we find an allowed region for the light gravitino, $m_{3/2} < 1$ keV,

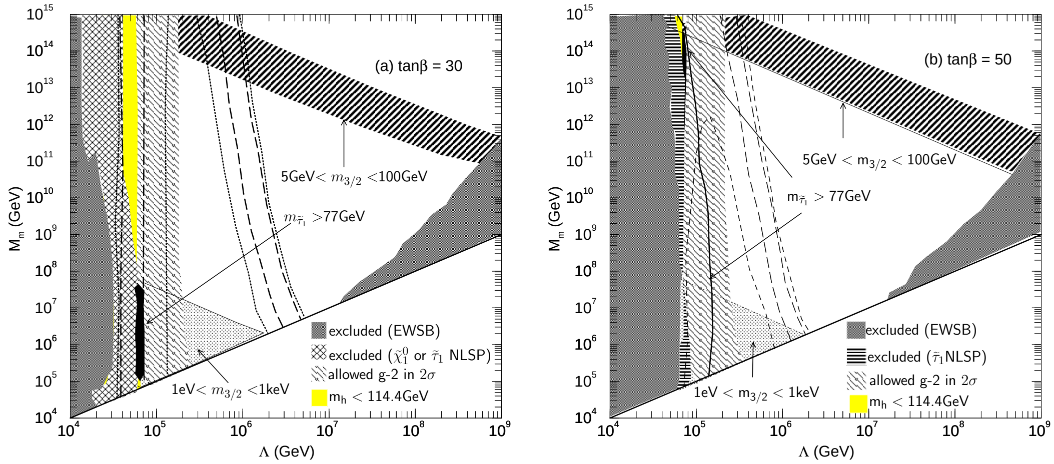

Figure 3: Constraints on the (Λ, M_m) plane from the electroweak precision measurements and the muon $g-2$ experiments for $\tan\beta = 30$ (a) and 50 (b). The gravitino mass range is shown for $1\text{eV} < m_{3/2} < 1\text{keV}$ and $5\text{GeV} < m_{3/2} < 100\text{GeV}$. The enclosed regions by the dotted lines give $\Delta\chi^2 < 4$, while those by the long-dashed lines give $\Delta\chi^2 < 1$. The 2-σ allowed region of the muon $g-2$ experiments is shown explicitly. In the enclosed region by the thick solid-line in (b), the $\tilde{\tau}_1$ mass satisfies the direct search limit of the NLSP, *i.e.*, $m_{\tilde{\tau}_1} > 77\text{GeV}$.

where constraints from the muon $g-2$, the electroweak precision measurements, and the direct search for the $\tilde{\chi}_1^0$ NLSP are satisfied simultaneously. However the allowed region is significantly reduced if the lower mass bound on the lightest Higss mass is given by $m_h > 114.4\text{GeV}$.

In Fig. 3, we show constraints on the model parameter space for $\tan\beta = 30$ (a) and 50 (b). For $\tan\beta = 30$, we find that, in a sizable region, the lighter gravitino is consistent with all the experimental constraints. The heavier gravitino, however, is again disfavored because of the lower mass bound on the stau NLSP from collider experiments. Fig. 3(b) shows that the fit to the electroweak precision data at the lighter gravitino region could be worse ($\Delta\chi^2 > 4$) than the case for smaller $\tan\beta (\leq 30)$. For the heavier gravitino, there is a very small region which is compatible with the bounds from the stau NLSP and the muon $g-2$. From these analyses, we find that the lower mass bound on the stau NLSP gives the most stringent constraint on the heavier gravitino, which could be allowed only for large $\tan\beta$, say, $\tan\beta \sim 50$.

We have so far performed our analysis by fixing the parameters k and N_m in (2) to be unity. It may be helpful to mention the k or N_m dependences of our

analysis. First, the k parameter is related to the gravitino mass through (3). If k is smaller than 1, the gravitino mass increases for fixed values of Λ and M_m. This means that the gravitino mass range on the (Λ, M_m) plane in our study is lowered for $k < 1$, in parallel with the range for $k = 1$. It is easy to see that the constraints on both the heavier and lighter gravitinos are not altered so much for $k < 1$. The dependence on N_m of the result is rather complicated because it reflects the detail of the SUSY breaking sector. In general, the soft SUSY breaking parameters tend to be large as N_m increases, so that the constraints on (Λ, M_m), *i.e.*, the NLSP mass, may be weaker for $N_m > 1$.

In summary, we have studied constraints on the model parameter space of GMSB taking into account the muon $g-2$ experiments, the electroweak precision measurements and the direct search experiments on the NLSP. The main interest of our study is in the influence of these experimental results on the allowed gravitino mass scales which are obtained from the cosmological gravitino problem. Assuming no entropy production mechanism below the reheating temperature of the inflation, we focused on two different gravitino mass scales, $m_{3/2} <$ 1keV [2] and 5GeV $< m_{3/2} <$ 100GeV [4]. We find that both possibilities are disfavored from the muon $g-2$ data and/or the NLSP direct search experiments for $\tan\beta = 3$. The light gravitino mass range could be allowed by these experiments in the small parameter region for $\tan\beta = 10$. However it is significantly reduced if $m_h >$ 114.4 GeV is used as the lower mass bound on the lightest Higgs boson. For $\tan\beta > 30$, the light gravitino mass is compatible with the low-energy experiments in sizable parameter regions. On the other hand, the heavier gravitino is strongly disfavored by the lower mass bound on the stau NLSP and the muon $g-2$ experiments. It could be allowed only if $\tan\beta$ is large enough, say, $\tan\beta \sim 50$. The possibility of the heavier gravitino, therefore, is pushed to a small corner of the parameter space.

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